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Analysis of Volcanic Development Model and Main Controlling Factors of Oil Distribution in the Third Member of Shahejie Formation in Zaoyuan Oilfield

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Abstract: In order to clarify the influence in the volcanic mode and structure on the oil reservoirs, the volcanic reservoir characteristics, volcanic eruption pattern, and volcanic eruption period of the third member of the Shahejie formation in the Dagang Oilfield Zao35 fault block are studied by combining logging, 3D seismic, and production data, and to provide geological basis for the subsequent development of volcanic reservoirs. The results show that the volcanic body of the Zao35 fault block is jointly controlled by the fissure-centered eruption mode, and there are three strings of bead-shaped eruption centers as well as a fault overflow channel. Based on the seismic response characteristics, the volcanic rocks can be divided into three main eruption cycles. Moreover, combined with the relatively stable mudstone interlayer encountered by the single well, it can be further divided into eight volcanic eruption periods. There are three different lava units in the overflow facies of each stage, namely thick layer dense basalt, basalt with pores developed at the top and dense at the bottom, and basalt with pores developed at the top and dense in the middle. Influenced by the volcanic development model, the oil is mainly distributed in the volcanic reservoir on the slope belt between the central eruption and the fracture eruption. Affected by volcanic eruption periods, the pore basalt at the top and bottom of each period controls the distribution of the oil reserves. Therefore, the thick layer stomatal basalt located between the two eruption modes is the key target of the next development.

Keywords: volcanic reservoir; eruption mode; division of periods; volcanic lithofacies; Zao35 fault block

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1. Introduction

Volcanic reservoir is a special oil reservoir, which can form a high-quality reservoir with good oil storage property in the process of magmatic condensation diagenesis. More than 300 volcanic oil reservoirs have been found in the world [1–10]. It has been found to varying degrees in most basins in China. At present, the accumulated proven geological reserves of oil have reached several hundred million tons of crude oil and several trillion cubic meters of gas. Effective reservoirs of volcanic rocks with large and stable distribution in the deep Songliao Basin have now been discovered, breaking the traditional understanding that volcanic rock formations lack effective reservoirs [11–15]. After discovering the potential of volcanic reservoirs, the current status of volcanic oil and gas resources is analyzed with respect to the geological and distribution characteristics of volcanic reservoirs in China, and the future blocks to be discovered and resource prospects are predicted [16,17], showing the great exploration and development prospects of volcanic reservoirs.

The development of volcanic reservoirs has the advantages of large reservoir thickness, more geological reserves and high single-well capacity, but it is also accompanied by the problems of complex reservoir distribution, unclear development pattern and scattered oil distribution. Previous studies on volcanic rocks in the Zao35 fault block mainly focused on the lithology and lithofacies classification [18–21], reservoir distribution prediction [22–25], fracture distribution prediction [26], and development effect analysis [27–33], and with a relatively low level of the cognizance of volcanic development mode and internal structure of volcanic reservoirs in this area. However, the study on volcanic rock characteristics and single well measures alone cannot provide effective references for subsequent development. Volcanic development mode is a summary of volcanic channel types, volcanic facies types, and eruption periods. Therefore, in the process of volcanic reservoir development, it is necessary to clarify the development mode of volcanoes and the influence of internal structure on the oil distribution.

To solve this problem, the volcanic reservoir in the third member of the Shahejie formation of the Zao35 fault block in the Candong depression is studied as an example, starting from the internal structure of the volcano. Therefore, clarifying the eruption pattern of volcanoes, facies distribution and the controlling factors of lithological oil reservoirs in the main reservoir is the first work to summarize the characteristics of oil reservoir distribution, which has guiding significance for the development of subsequent reservoirs.

2. Regional Geological Setting

The Zao35 fault block is located in the downthrown side of Li Tianmu fault in Kongdian structural belt of Cangdong sag, Huanghua depression, Bohai Bay Basin (Figure 1). The intense tectonic movement formed the complex fault block in Huanghua depression, accompanied by multi-stage magmatic activities, and formed multi-stage volcanic rocks in the third member of Shahejie formation. The Cangdong sag belongs to the Cenozoic faulted lake basin of the Bohai Bay Basin [34,35]. Zao35 fault block is a small single fault lake basin developed in the Kongdian structural belt. It presents a saddle structure as a whole, with a fault–backlash structure in the northwest and southeast directions and the development of several north-east normal fault. During the Paleogene, strong tectonic activities occurred in Huanghua depression [36,37], and accompanied by multi-stage magmatic activities, multi-stage thick layer basic extrusive rocks were formed in the third member of Shahejie formation of the Zao35 fault block. Basalt is the main lithology of this reservoir. Zao35 fault block is a fracture-pore type dual medium volcanic oil reservoir, which belongs to a special oil reservoir with a burial depth of 1531–1635 m. The oil-bearing section is the third member of Shahejie formation.

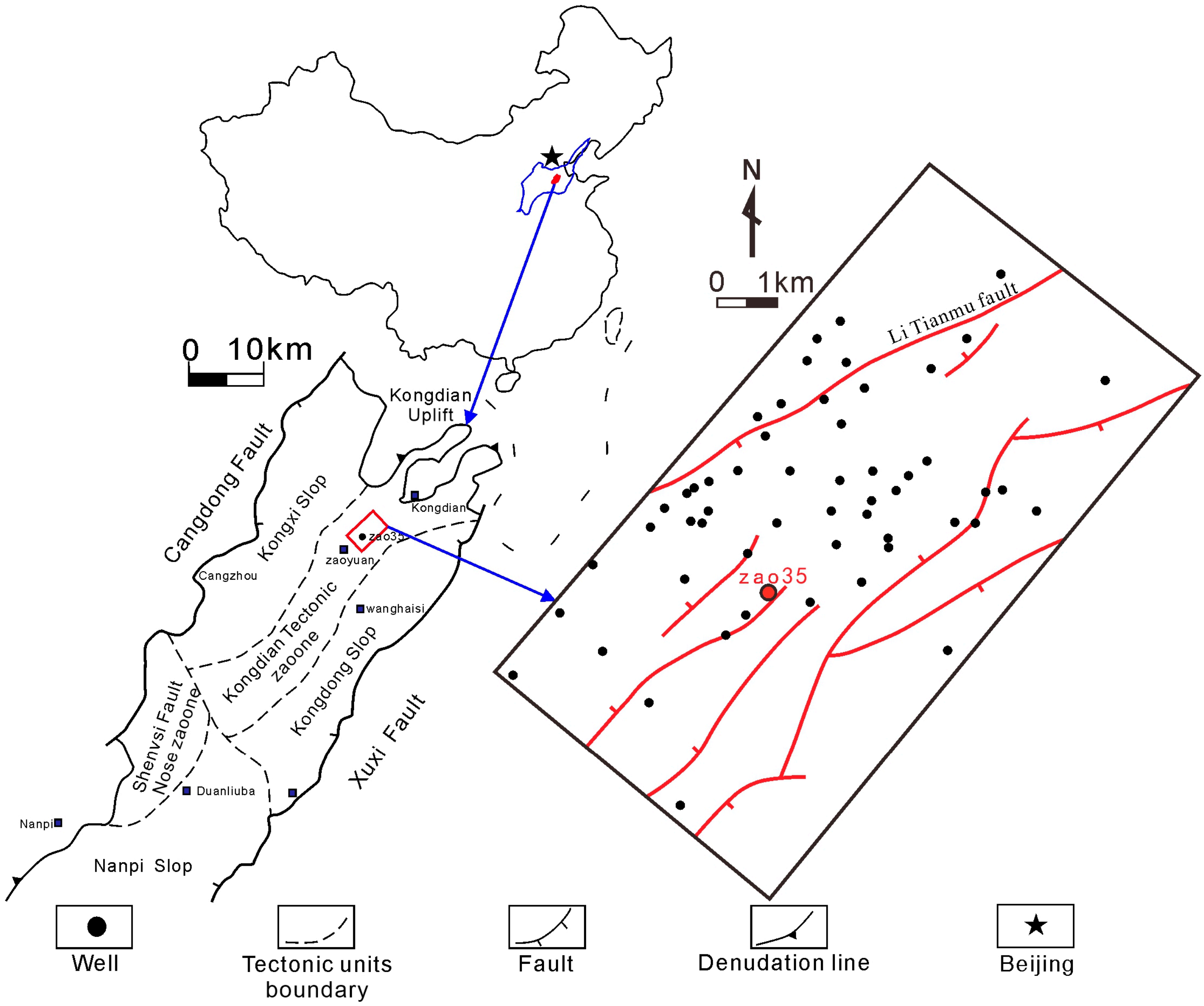

Figure 1. Tectonic setting and location of the Zao35 Oilfield.

3. Samples and Methods

Since the development and production of the study area in 1995, 56 wells have been drilled, including 5 core wells, with a minimum planar well spacing of 500 m, and complete single well logging data. The average stratigraphic depth of the Sand III section is 1500 m, and there are 3D seismic data with accuracy of 25 × 25 m and seismic main frequency of 25 hz, which can respond to the vertical distribution of single-phase volcanic rocks. Cores, logs, seismic, and dynamic production data were used in this study.

Volcanic development patterns determine the development of volcanic reservoirs by combining seismic and logging data, the study of volcanic development patterns and period distribution is carried out, and the oil-bearing distribution between different volcanic patterns in the plane and within different periods in the vertical direction is clarified. By combining three volcanic units, the reservoir distribution is determined by combining lithological characteristics.

4. Characteristics of Volcanic Reservoir

4.1. Lithological Characteristics

According to the analysis of thin section in well Zao 78 and Jun 21–23, the volcanic rocks in the Zao35 fault block can be divided into two types: explosive volcanic clastic rocks and overflow lava. The volcanic clastic rocks in this area are mainly volcanic breccia formed by the early solidified basalt near the volcanic channel that was blown up during the eruption, and partly tuff formed by volcanic ash. The volcanic lava is mainly basalt formed by the overflow of volcanic magma. Among them, the volcanic lava is basalt, including stomatal basalt and dense basalt (Figure 2a,e), and some dense basalts develop amygdaloidal structures (Figure 2d). Pyroclastic rocks include tuff and volcanic breccia (Figure 2b,c); thick lacustrine mudstone is developed during volcanic intermittence (Figure 2f). The effective reservoir of volcanic oil reservoirs in the study area is the large-scale thick layer bas-alt communicated by fractures.

Figure 2. Typical core photos of main rock types in the Zao35 fault block volcanic reservoir. (**a**) stomatal basalt, Jun 21–23, 1591 m; (**b**) volcanic breccia, zao78, 1519 m; (**c**) tuff, zao78, 1506.67 m; (**d**) almond basalt, Jun 21–23, 1602.33 m; (**e**) dense basalt, Jun 21–23, 1600 m; (**f**) mudstone, Jun 21–23, 1637 m.

4.2. Pore Types and Characteristics

The volcanic rock reservoir pore space in this area is complex and diverse, with pores and fractures. According to the macroscopic observation of core, the analysis results of rock and cast thin section, and the type of reservoir space, the reservoir space of Zao35 is divided into two categories: pore and fracture [38]. Pore is the main reservoir space, while fractures are the main channels for the oil migration and accumulation.

① Pore: the pore in the volcanic rocks in this area can be directly observed by the naked eye, with pore diameter being between 0.5 mm and 2 cm (Figure 3a), and the average diameter is 8 mm. It is widely distributed in stomatal basalt. Stomatal basalt is the most widely distributed in volcanic reservoir of the Zao35 fault block (Figure 3a).

② Almond pores: Almond pore is a kind of pore structure, which is a structure formed by filling the pores inside the volcanic rocks with secondary minerals, and the basalt that develops this structure is called almond basalt. Pores are always filled with secondary minerals, leaving part of the space to form almond pores. The almond was poor in oil content (Figure 3b).

③ Inner pores of almond: pores in Almond basalt are filled with chalcedony (partially calcite) (Figure 3c,d). Pores are rare or very fine, pores are not developed, and most of them do not contain oil.

④ Intergranular pore: formed by intergrain compaction remnants. It is mainly developed at the top and bottom of lava, mainly distributed in the pyroclastic rocks near the main crater of well Zao 78. It is generally oil-bearing and non-main reservoir, with a small pore diameter, generally 0.01–1 mm.

⑤ Intergranular pores: a large number of volcanic breccia pores are developed in the volcanic breccia in the volcanic rock reservoir of block Zao35, and the intergranular pores are formed by mutual support of volcanic breccia. The oil saturation can be significant for these pores.

⑥ Intergranular pores and intracrystalline pores: pores formed in the process of mineral crystallization or recrystallization. It is small in scale and mainly in porphyry structure. The phenocrysts are mainly plagioclase and saponite (Figure 3f). The matrix has intergranular structure (Figure 3e). The irregular framework composed of long plagioclase is filled with fine pyroxene, magnetite, and dark minerals. Some of the dark minerals are chloritized and often serve as a non-permeable interlayer within the volcanic eruption period. Most of them do not have the ability to store the oil.

Two types of structural fractures and diagenetic fractures are mainly developed in the volcanic rocks in this area, which are distributed in a grid shape (Figure 3g). The storage space is small, and it mainly serves to connect pores.

① Structural fractures: structural fractures are mainly micro fractures produced by volcanic rocks under the action of structural stress. They are highly developed near the fault, relatively flat, and mostly high angle fractures. Since NW-SE faults are mostly developed in this area, structural fractures are mostly developed (Figure 2b), which is the main channel for connecting reservoirs (Figure 3h).

② Diagenetic fissure: diagenetic fissure is a condensation contraction fissure (Figure 3i), which is a contraction microfracture formed in the process of magma condensation and crystallization. Macroscopically, it is a columnar joint and planar fracture, and it is a secondary channel connecting the reservoir.

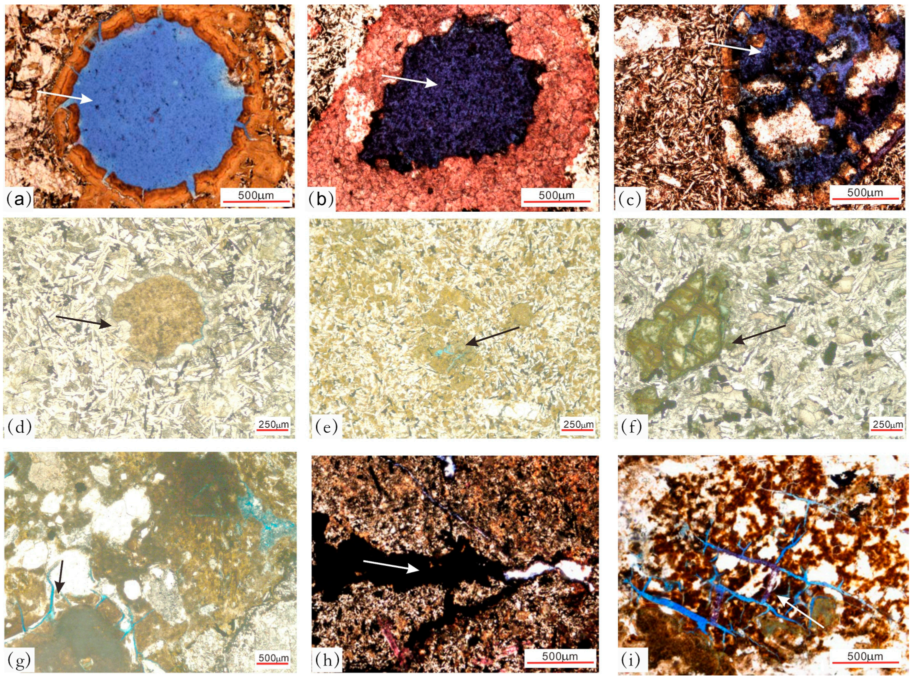

Figure 3. Lithological characteristics and pore characteristics of the Zao35 fault block. (**a**) pore; (**b**) almond; (**c**) almond internal pore; (**d**) almond internal pore; (**e**) interstitial structure; (**f**) macular structure; (**g**) intergranular microcracks; (**h**) structural joint; (**i**) diagenetic contraction joint.

5. Volcanic Development Model and Eruption Period

5.1. Volcanic Development Model

The lithofacies of volcanic rocks in the study area can be divided into three categories: volcanic channel facies, explosive facies, and overflow facies, of which the most important lithofacies is overflow facies. Volcanic channel facies are mainly columnar in seismic section (Figure 4a). Because the occurrence of volcanic channel is different from that of surrounding strata, the volcanic channel facies of the Zao35 fault block shows a nearly vertical or upward divergent reflection profile on the seismic section, and the internal features are medium weak amplitude, high frequency, and poor continuity. Due to the poor sorting and mixed size of volcanic clasts in the explosive facies, the plane facies change is fast, and the seismic section is mostly characterized by chaotic reflection of medium to weak amplitude and medium poor continuity. The GR curve is jagged and the acoustic wave curve has a high value distribution (Figure 4b). The lava in the overflow facies has good continuity and stable distribution. On the seismic section, it mostly shows the seismic reflection characteristics of medium to strong amplitude and relatively good continuity. The parallel and sub parallel seismic reflection structure is mostly layered. The GR curve is box-shaped, and the acoustic wave curve has a low value distribution (Figure 4c).

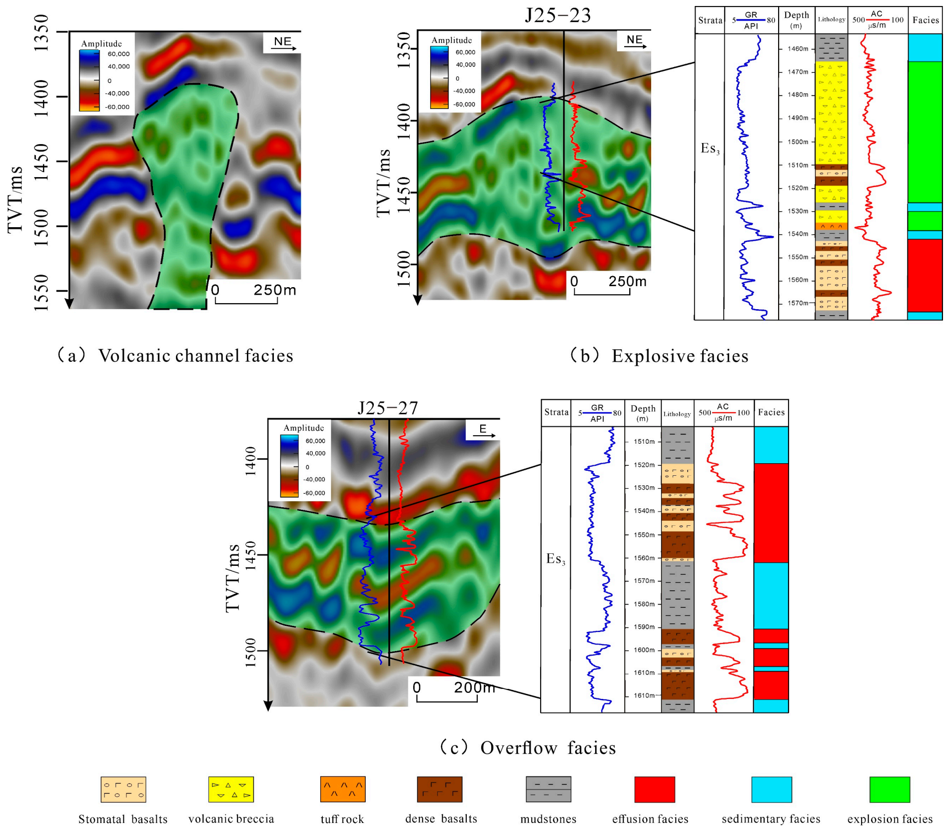

Figure 4. Seismic facies and logging facies characteristics of different lithofacies of the third member of the Shahejie formation. (**a**) volcanic channel facies; (**b**) explosive facies; (**c**) overflow facies.

Huanghua depression is in a strong fault depression period during the sedimentation period of the third member of the Shahejie formation. The volcanic activity of the Zao35 fault block experienced a quiet fissure overflow—intermittent effusion—multi center fissure eruption. According to the characteristics of seismic data, it is determined that there are two kinds of eruption channels for the magma in this area. The volcanic rocks in the third member of Shahejie formation of the Zao35 fault block are divided into fissure type eruption and central type eruption.

Three central volcanic channels are mainly developed in the Zao35 fault block. The seismic reflection event axis is shown as weak amplitude reflection, in the form of upward divergent umbrella shaped and nearly vertical columnar, distributed parallel to the strike of the fault zone, and the scale is one large and two small (Figure 5).

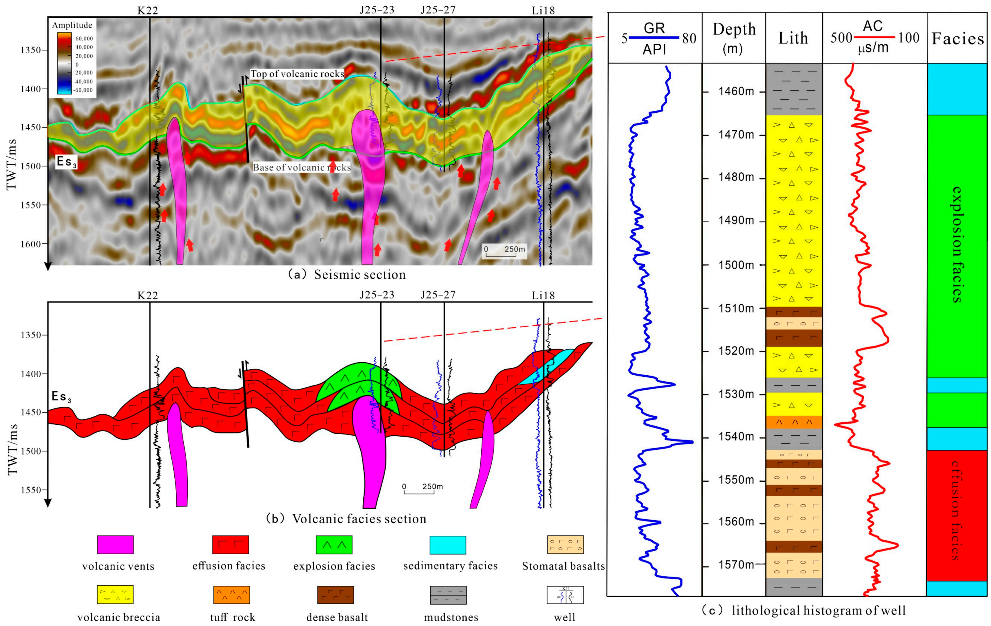

Figure 5. Sectional view of the central volcanic channel in the Zao35 fault block. (**a**) original seismic section; (**b**) volcanic lithofacies section; (**c**) lithological histogram of well.

In addition to three central eruptive channels, there are also fissure eruptions with faults as volcanic channels. The volcanic channel width of volcanic fissure type eruption in the Zao35 fault block is small, and the seismic shape is wedge-shaped. Affected by the fault tendency, the volcanic rock mass is developed on the south side of Li Tianmu fault (Figure 6).

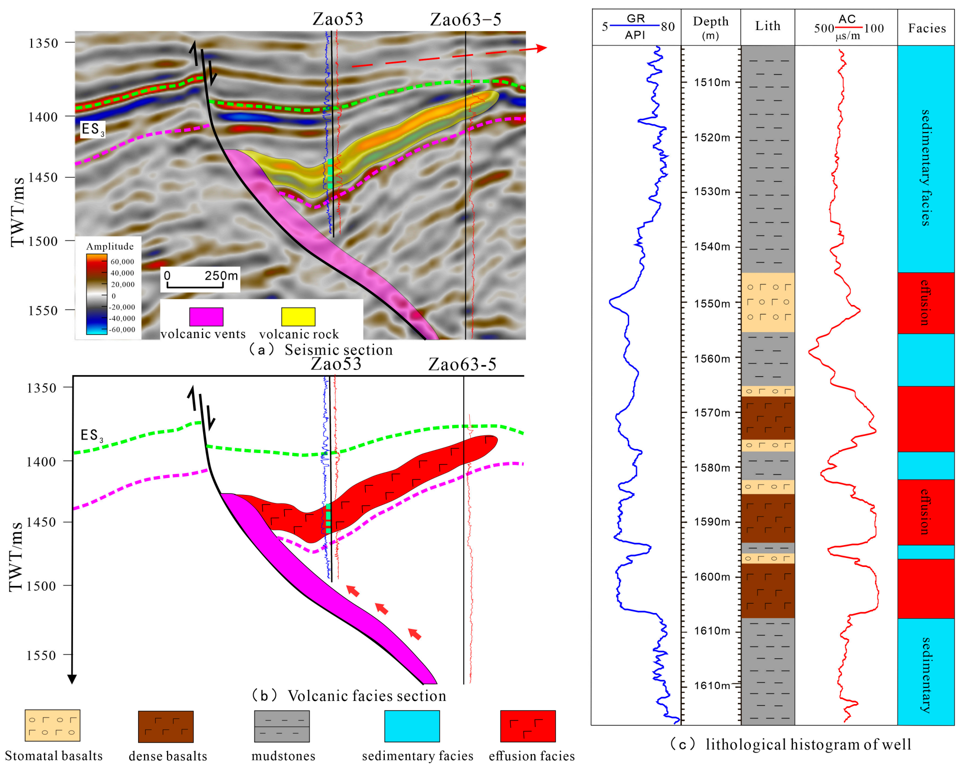

Figure 6. Sectional view of the of the fractured eruption of the Li Tianmu fault. (**a**) original seismic section; (**b**) volcanic lithofacies section; (**c**) lithological histogram of well.

Based on the two eruption modes of the volcanoes in the area and the lacustrine shell fossils and algal fossils [39] in the mudstone of the target layer, it is determined that the volcanoes in the study area are multi-stage volcanic (Figure 7) formed by the underwater fissure eruption along the northern Li Tianmu fault and the central eruption of multiple volcanic channels parallel to the fault (Figure 8). The lacustrine mudstone interlayer is developed in each stage, and the volcanic rocks are mainly overflow facies basalt (Figure 8).

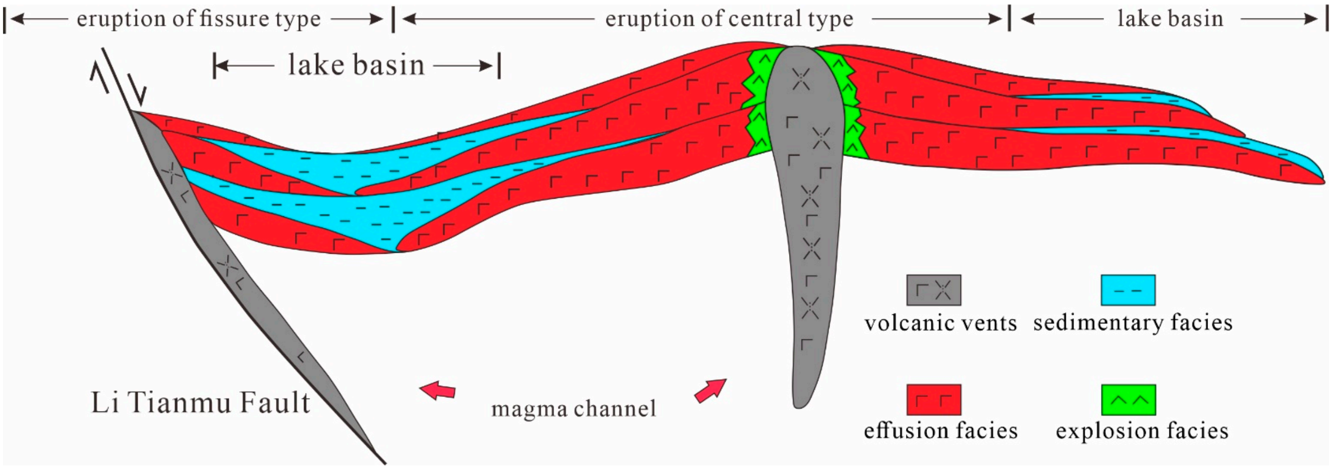

Figure 7. The volcanic development pattern of the Zao35 fault block.

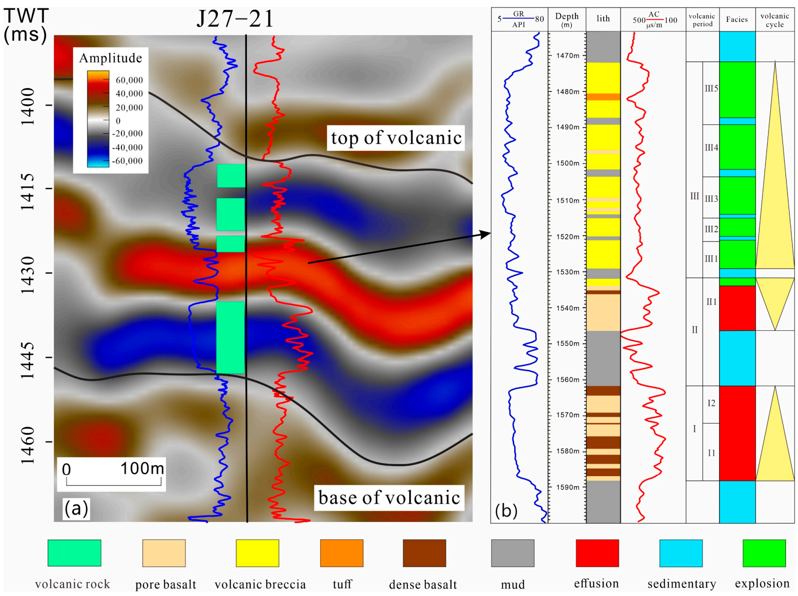

Figure 8. Division results of volcanic eruption stages in June 27–21. (**a**) Jun 27–21 seismic profile; (**b**) division of volcanic eruption periods of well Jun 27–21.

5.2. Volcanic Eruption Cycles and Periods

The basalt is characterized by low natural gamma, low acoustic time difference, high density, and low neutron value logging response. There are thick layers of stable mudstones between each volcanic eruption cycle, and there is a large acoustic impedance difference between the volcanic rocks and mudstones. The lithological interface is a strong seismic reflection interface. According to the two layers of stable mudstones developed in the typical Jingjun 27–21 well and the facies 3 seismic response, the volcanic rocks in the study area are divided into three volcanic eruption cycles (Figure 8). The volcanic rocks in the study area are divided into early stage (stage I), middle stage (stage II), and late stage (stage III) (Figure 9a).

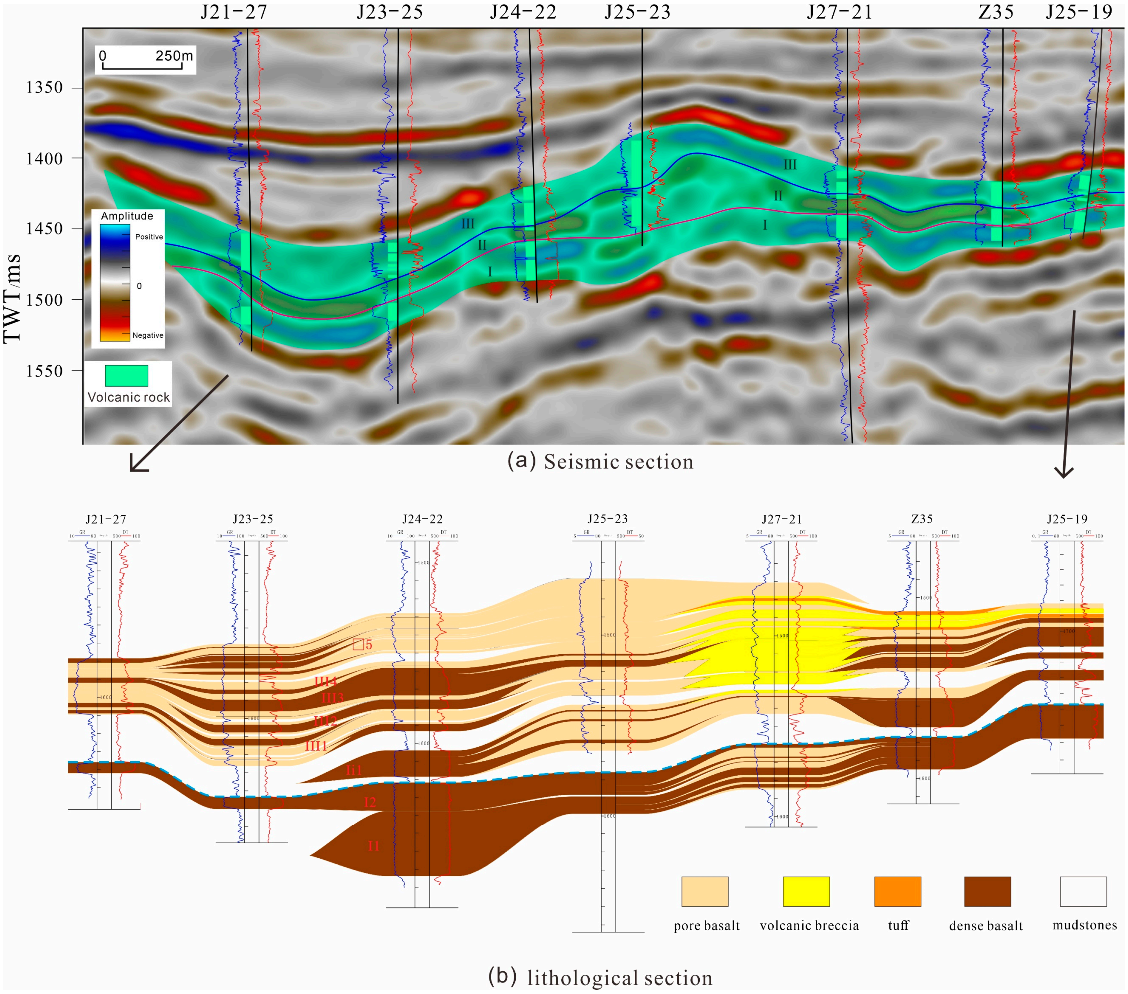

Figure 9. Sections of the volcanic eruption stages of the Zao35 fault block. (**a**) response characteristics of volcanic stages on seismic profiles; (**b**) lithological distribution characteristics within the substages.

In addition to seismic data, mudstone interbeds deposited between periods can be used as the main basis for subdivision of volcanic periods. According to the single well petrological data of 42 volcanic rocks drilled in the study area and the volcanic rock eruption mode, seven stable mudstone segments can be identified in the volcanic rock section drilled under the constraint of three volcanic rock seismic periods, and the three eruption cycles of the volcanic rocks in the study area are subdivided into eight substages (Figure 9b).

The eruption scale of volcanic rocks in this area shows a trend of weakening first, then strengthening, and finally weakening from early to late, which is consistent with the three eruption cycles of volcanic rocks (Figure 10). When the magma supply is sufficient, the fissure type and three central volcanic channels are opened to form large-scale thick volcanic rocks. When the magma supply is insufficient, only the fissure type and 1–2 central volcanic channels are opened. In the early stage of volcanic eruption (stage I), the overall thickness of volcanic rocks is relatively thin, and two stages are developed. The development areas of substage I 1 and substage I 2 are 0.78 km^2 and 0.75 km^2, respectively, with an average thickness of 14 m and 8 m. In the middle stage of volcanic eruption (stage II), only one stage was developed. The thickness of volcanic rocks was thin, with an average thickness of 7.5 m. During this period, a large number of thick lacustrine mudstones were deposited, with a maximum thickness of 19 m. At this time, the volcanic activity entered a relatively quiet period. The late stage of volcanic eruption (stage III) is the most active and developed (substage III 1–III 5), with a development area of 0.79 km^2. The volcanic activity in this period is the most intense and frequent, forming multi-stage volcanic rocks (Figure 10). The average thickness of substage III 1–III 5 is 8–11 m, of which the distribution area of substage III 3 is the largest (0.76 km^2), and the distribution area of substage III 5 is the smallest, with a development area of 0.45 km^2 (Figure 11).

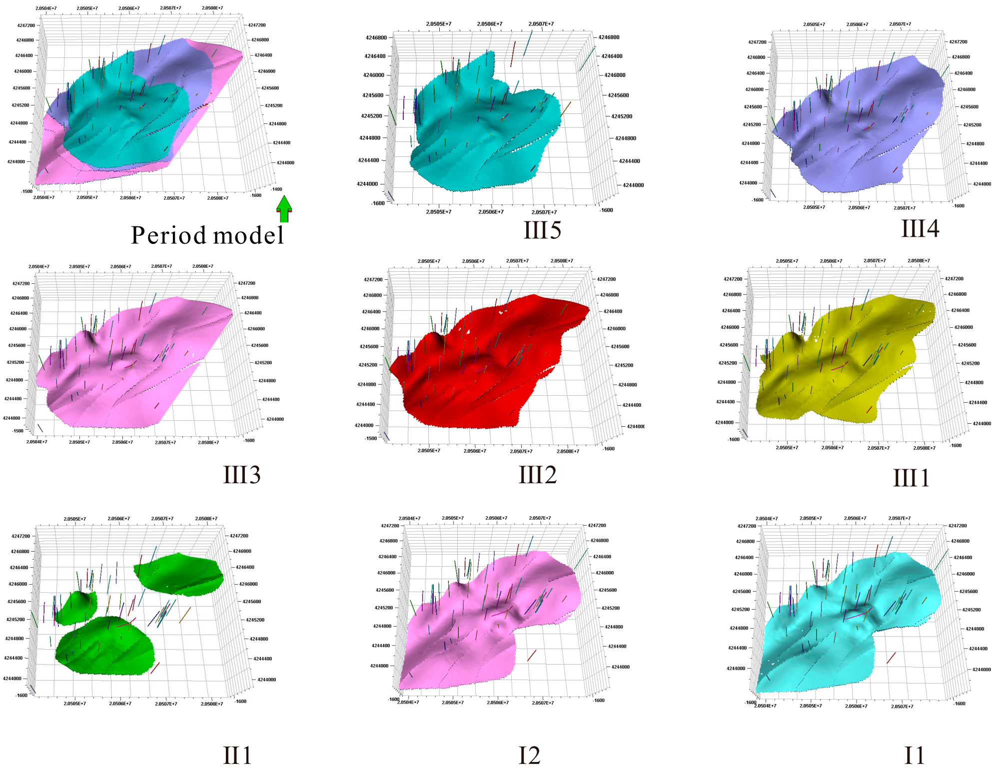

Figure 10. Wells section of volcanic stages division in the Zao35 block.

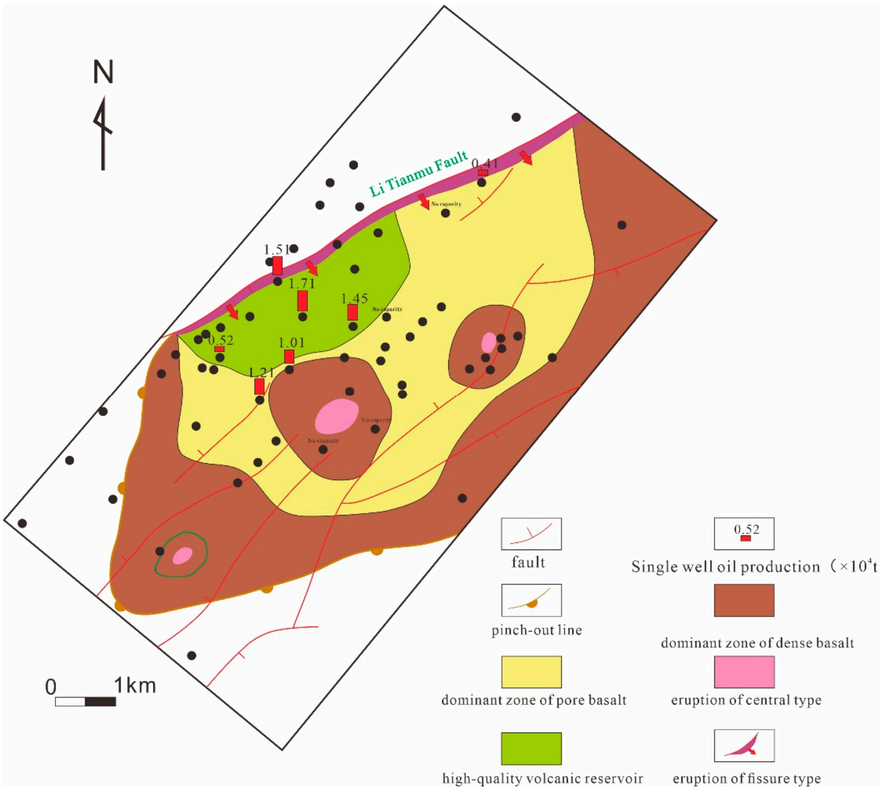

Figure 11. Distribution map of single well cumulative production in the Zao35 fault block.

6. Discussion

6.1. The Volcanic Eruption Pattern Controls the Horizontal Distribution of Oil

The central eruption of the Zao35 fault block is overflow eruption, which results in the dominant position of overflow facies in spatial distribution. Combined with the cumulative production data of single well, it is shown that the volcanic breccia intergranular pores of explosive facies are effective volcanic reservoirs, but the distribution of explosive facies is limited, and the thickness and distribution range of volcanic breccia and tuff are low, which cannot be used as main reservoirs. The tuff is relatively loose and difficult to preserve in situ, and is more likely to move under the action of flowing water to form sunken tuff in the lake basin background. Secondly, in the overflow facies, the stomatal development ratio of different parts is different. On the plane, stomatal basalts show the distribution characteristics of first increasing and then decreasing in the direction away from the crater: the pores near the crater are small and isolated, the pore at the slope of the volcano are fully developed, and the pore at the far crater are few. At the time of volcanic eruption, the volcanic center was a hydrothermal active zone, and the pores near the crater were filled to a high degree, forming large-scale almond basalt with large thickness, which was difficult to be communicated by faults on a large scale, and most of them were ineffective reservoirs. However, the well-developed pores in the middle slope of the volcano are easily communicated by fractures to form high-quality oil reservoirs. The volcanic lava gradually thins in the direction of the volcanic rim, and the gas is gradually not easily preserved inside the volcanic magma, so the gas pores gradually decrease in the direction away from the crater, and the porosity decreases again. This is proved by combining the advantageous planar distribution of stomatal basalt, the distribution of high-quality reservoirs, and the productivity distribution of single wells. The productivity of single wells in the middle of fracture type eruption and central type eruption is mostly high-yield wells, while the productivity of single wells near volcanic channels is mostly non productive wells, as shown in Figure 11.

The influence of fracture type eruption of the Zao35 fault block on the volcanic oil reservoirs is mainly reflected in the distribution of lithofacies and reservoir reconstruction. Fracture type eruption greatly increases the thickness and distribution range of overflow facies lava. The basic magma with low viscosity and good mobility is ejected along the fault zone, and the volatile gas rich magmatic activity produces a large number of stomatal basalts. Secondly, the litianmu fault (fracture channel) is a synsedimentary fault after the volcanic eruption [40]. The fault activity is strong and the time is long, resulting in a high degree of fault development in the volcanic rock mass. The structural fault has a significant effect on the gas pores and pore-connectivity modification, forming a fracture-pore type permeability storage mode, which greatly improves the connectivity of primary pores in the volcanic rock mass. Therefore, the volcanic rock reservoir near the fault has good physical properties. The single well productivity near the large fault in the northwest indicates that the oil is mostly distributed along the fault.

Combined with the two eruption modes and the cumulative production distribution of single wells in this area, the oil in this volcanic reservoir is mainly distributed in the slope zone of overflow facies formed by central eruption and near the fault of fracture type eruption.

6.2. Volcanic Eruption Periods Control the Vertical Distribution of Oil

In the study area, there are certain lithological changes in the volcanic rock eruption periods. In conjunction with Dong Dong's (1991) study [41] on intermediate basal volcanic lavas, after the magma is ejected from the surface, the pore structure is formed at the top and bottom of the volcanic rocks due to the decrease in pressure and temperature (contact with the ground at the bottom and air at the top), while the middle of the thick volcanic rocks cannot form or discharge the gas due to the cooling of the top and bottom of the rocks, resulting in the formation of a dense volcanic rock unit in the middle, so the pores of the volcanic rocks form a vertical distribution pattern of increasing porosity from top to bottom, then decreasing and finally increasing. The upper part of the overflow facies has relatively developed pores, and the thickness of the pore basalt is large, which is a dominant reservoir; in the middle of the overflow facies, the porosity of the lava is low and thick dense basalt is formed; the lower part is relatively thin pore basalt, and its physical property is inferior to that of the upper reservoir. For the the oil reservoir in the study area, there are three different basalt units in the single-stage overflow facies, namely, thick layer dense basalt, basalt with pores developed at the top and dense at the bottom, and basalt with pores developed at the top and dense in the middle (Figure 12). For vertically thick basalt reservoirs, the main oil-bearing horizons are mostly located at the top and bottom of basalt, and the central part is dense and generally does not contain oil.

The lithology of volcanic rocks controls the development of primary pores and provides the basis for later reformation. Among them, the pores of volcanic rocks at the upper and bottom of the single-stage overflow facies are relatively developed, and the oil bearing property is good, which can reach the oil-rich level (Figure 13). In the middle of the single-stage overflow facies, the rocks are dense, the primary pores are not developed, and the foundation for later transformation is lacking. It is a non-permeable interlayer of the whole volcanic in the oil reservoir. Therefore, in this volcanic rock reservoir, the top and bottom of thick layer basalt in this period are the main oil storage areas.

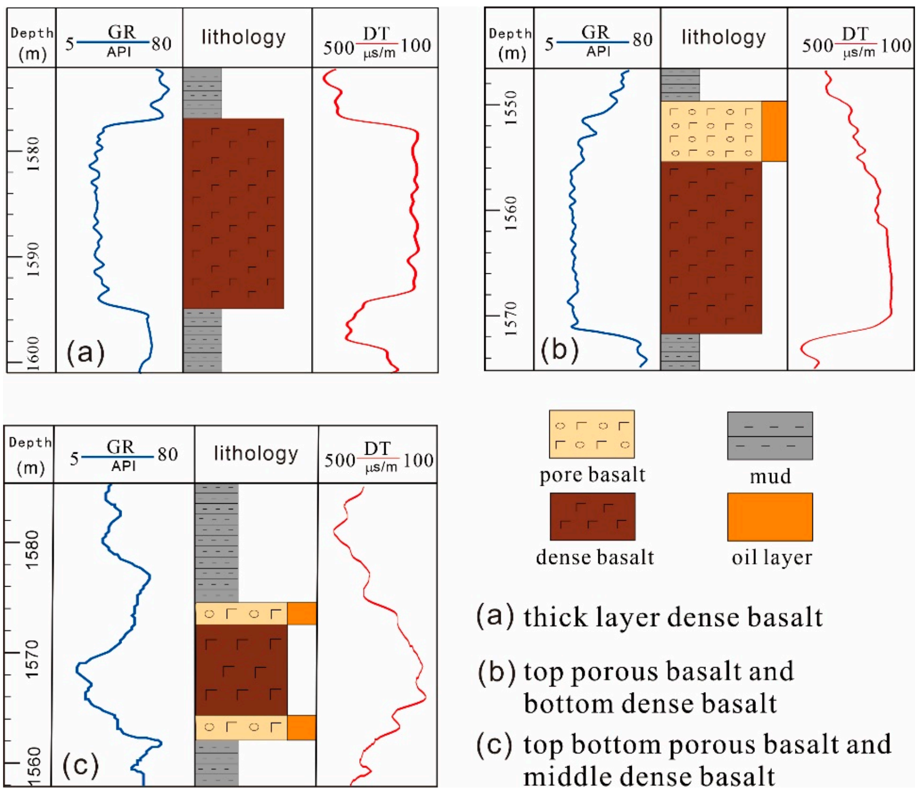

Figure 12. Log interpretation diagram of the lava unit in the fault block Zao35.

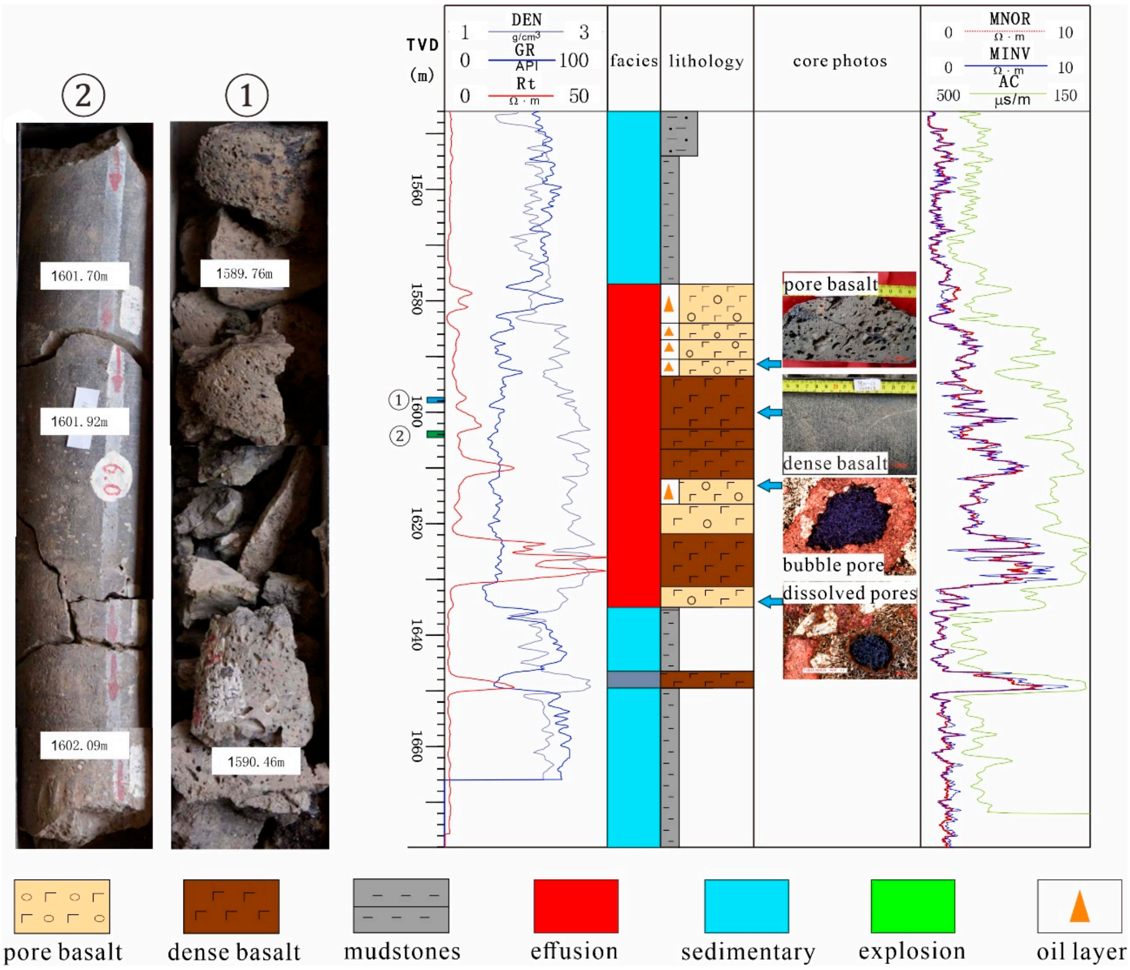

Figure 13. The comprehensive histogram of Jun 21–23 and the characteristics of rock cores and slices.

6.3. The Thickness of Pore Basalt Determines the Potential Distribution of the Oil in Volcanic Rocks

The proportion of overflow facies stomatal basalts to dense basalts also differ greatly between different time periods. Stomatal basalts are less developed in the early stage (I 1 and I 2) and the thickness increases in the middle stage (II 1) and is more developed in the later stage of volcanic eruption (III 1–III 5). Although the early (I 1 and I 2) volcanic rocks have a certain thickness, there are fewer pores caused by volatile gas release during lava condensation, and their degree of favorable reservoir development is low, which is not suitable for being the main development objective. This is due to the differences in the volatile gas content contained in the lavas of different time periods. Within the period, stomatal basalt is most widely distributed but more than dense basalt (non-permeable interlayer) forms interbedding. In addition, volcanic breccia is only locally developed, concentrated near the main crater, with increased thickness at the top and low tuff development (Figure 10).

The volcanic reservoirs in the study area are the oil reservoirs without boundary and bottom water, and the distribution of the oil is mainly controlled by lithology. The pores communicated by micro cracks in the porous basalt are the most important oil storage space. The geological reserves of single-stage crude oil are positively correlated with the effective reservoir development thickness, mainly with the thickness of stomatal basalt. According to the distribution of lithologic of each stage, the geological reserves of stage III 4 and stage III 5 with the highest development degree of stomatal basalt account for 40% of the whole oil reservoir. However, the thickness of stomatal basalt in the early stage (I 1, I 2) and the middle stage (II 1) of volcanic eruption is thin, and the geological reserves only account for 9% (Figure 14).

By summarizing the influence of three factors, namely, volcanic development pattern, volcanic phase, and volcanic lithology, on the oil distribution inside volcanic reservoirs, the main objectives of subsequent reservoir development are clarified, which provides a basis for the development of the same type of volcanic reservoirs. However, the internal structure of volcanic reservoirs is complex and the eruption pattern of volcanic rocks is diverse, so in the process of volcanic reservoir research, the structural characteristics of the internal volcanic rocks should be clarified first, and the eruption pattern and phase of volcanic rocks should be clearly understood. In addition, the lithology of volcanic rocks also needs to be focused on, and the change of lithology is often accompanied by the change of oil content. For volcanic reservoirs with complex lithology, oil content analysis should be conducted by lithology to summarize the distribution pattern of different oil-bearing lithologies.

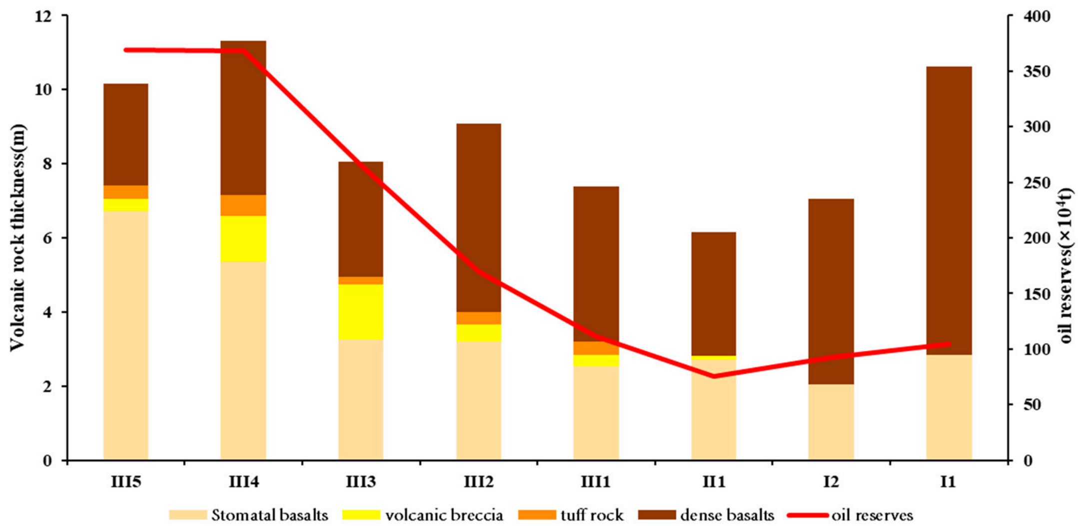

Figure 14. Distribution map of lithology and geological reserves at different stages.

7. Conclusions

(1) The volcanic rocks in the third member of Shahejie formation of the Zao35 fault block are jointly controlled by fracture and central type eruptions, and three central volcanic channels can be identified, of which one is the primary and two are secondary, showing a string of bead-shaped along the fracture zone. The Li Tianmu fault is a fissure type magma channel. The volcanic eruption mode determines the planar distribution of oil, which is mainly distributed at the slope reservoir of a central type eruption and in the reservoir near the fracture type eruption.

(2) The internal volcanic rock of the Zao35 fault block shows three periods of seismic response, which can be further divided into eight periods of volcanic eruption. There are three different basalt units in the single-stage overflow facies, which show the scale of stomatal development gradually decreasing away from the crater. The period of volcanic development determines the vertical distribution of the oil in volcanic rock reservoirs. In three different basalt units, the oil is mainly distributed at the top and bottom of thick basalt.

(3) The distribution of oil and gas reserves in volcanic reservoirs is highly correlated with lithology, and in this area, it shows a positive correlation with the distribution of stomatal basalt. Stage III 4 and III 5 with the largest thickness of stomatal basalt have the highest oil enrichment and are the key targets for the next development.

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